

A new determination of the orbit and masses of the Be binary system δ Scorpii

W. J. Tango,^{1*} J. Davis,¹ A. P. Jacob,¹ A. Mendez,¹ J. R. North,¹
J. W. O’Byrne,¹ E. B. Seneta² and P. G. Tuthill¹

¹*Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia*

²*Cavendish Laboratory, Univ. of Cambridge, UK*

XXXX XXXX

ABSTRACT

The binary star δ Sco (HD143275) underwent remarkable brightening in the visible in 2000, and continues to be irregularly variable. The system was observed with the Sydney University Stellar Interferometer (SUSI) in 1999, 2000, 2001, 2006 and 2007. The 1999 observations were consistent with predictions based on the previously published orbital elements. The subsequent observations can only be explained by assuming that an optically bright emission region with an angular size of $\gtrsim 2 \pm 1$ mas formed around the primary in 2000. By 2006/2007 the size of this region grew to an estimated $\gtrsim 4$ mas.

We have determined a consistent set of orbital elements by simultaneously fitting all the published interferometric and spectroscopic data as well as the SUSI data reported here. The resulting elements and the brightness ratio for the system measured prior to the outburst in 2000 have been used to estimate the masses of the components. We find $M_A = 15 \pm 7 M_\odot$ and $M_B = 8.0 \pm 3.6 M_\odot$. The dynamical parallax is estimated to be 7.03 ± 0.15 mas, which is in good agreement with the revised HIPPARCOS parallax.

Key words: binaries: spectroscopic — binaries: visual — stars: fundamental parameters — stars: individual (δ Sco, HR 5953) — techniques: interferometric

1 INTRODUCTION

The bright southern star δ Sco (HR 5953, HD143275; RA = $16^{\text{h}} 00^{\text{m}} 20^{\text{s}}.01$, $\delta = -22^\circ 37' 18''$) is listed in the Bright Star Catalogue (BSC) (Hoffleit & Warren 2001) as a B0.3 IV star. It is listed in the Sixth Catalog of Visual Binary Stars (Hartkopf & Mason 2006) as a spectroscopic triple and occultation quadruple system; however, the overwhelming evidence is that it is a binary system with very high eccentricity.

In 2000 Otero, Fraser & Lloyd (2001) observed a remarkable brightening of this star and since then it has exhibited irregular variability. It is now classed in SIMBAD as a B0.2 IVe star, and it has been suggested that it may be a γ Cas type variable (Otero et al. 2001).

We report here observations made with the Sydney University Stellar Interferometer (SUSI) from 1999 to 2007 that are consistent with the development of an optically thick circumstellar disk around the primary star and discuss the implications for our understanding of γ Cas variable stars.

The orbital elements for δ Sco have been determined both from interferometry and spectroscopy (see Section 2)

but the elements found by the the two techniques are inconsistent. Following Pourbaix (1998) we present a new analysis of the orbital and radial velocity (RV) data that simultaneously minimises the residuals in x , y and \dot{z} , where x , y are the cartesian coordinates of the secondary with respect to the primary projected onto the plane of the sky and \dot{z} is the heliocentric radial velocity of the secondary. This new solution is consistent with both the interferometric and spectroscopic data and allows us to estimate the masses of the A and B components of δ Sco as well as the dynamical parallax of the system.

2 OBSERVATIONS PRIOR TO 1997

2.1 Lunar occultation and interferometric observations

The binary nature of δ Sco was first reported by Innes (1901), who observed it during a lunar occultation in 1899. This work was largely forgotten until 1974 when δ Sco was rediscovered to be binary using lunar occultation (Dunham 1974), by interferometry with the Narrabri Stellar Intensity

* Email: W.Tango@physics.usyd.edu.au

Interferometer (NSII) (Hanbury Brown, Davis & Allen 1974) and by speckle interferometry (Labeyrie et al. 1974). Since then it has been regularly observed with speckle interferometry (see Hartkopf et al. 2006, for references).

Bedding (1993) observed δ Sco with the Masked Aperture-Plane Interference Telescope (MAPPIT). Using his measurement and the measures previously obtained with speckle interferometry he was able to calculate an orbit for the system. The MAPPIT data were also used to estimate the brightness ratio of the two components.

The orbital elements were recalculated by Hartkopf, Mason & McAlister (1996).¹ A revised orbit using more recent spectroscopic data has been calculated by Miroshnichenko et al. (2001) but it is clearly inconsistent with the interferometric data.

The accurate determination of the orbital elements using interferometry has proved to be rather difficult. Part of the reason is that β , the brightness ratio of the secondary to the primary, is approximately 0.2. For interferometric observations the signal-to-noise ratio (SNR) for the fringe modulation due to the binary (see equation (1)) is multiplied by a factor of $2\beta/(1+\beta)$ and for δ Sco this is approximately 0.3.

The other difficulty is the large eccentricity of the orbit ($e > 0.9$). It is apparent from Fig. 3 that there are no speckle observations near periastron since the two stars are too close to be resolved when using apertures of the order of 5 metres. The original motivation for this work was to observe δ Sco near periastron with SUSI using a baseline of 40 m (corresponding to an angular resolution of ~ 2 mas for an observing wavelength of 442 nm).

2.2 Spectroscopy and photometry

The BSC (Hoffleit & Warren 2001) noted that δ Sco is a spectroscopic binary with a period of approximately 20 days (see van Hoof, Bertiau & Deurinck 1963), although Levato et al. (1987) found a period closer to 80 days. More recent spectroscopy (see below) shows no clear evidence of a short period companion.

Prior to 1993 δ Sco had been regarded as a typical B star and was listed as a photometric standard in several catalogues (Slettebak 1982, 1985; Perry, Olsen & Crawford 1987). However, Cote & van Kerkwijk (1993) reported that the H α profile showed emission on the flanks of the absorption line and they proposed that it should be classified as a Be star. Bedding (1993) noted that this observation was made approximately 10 months after periastron and speculated that the two events might be related.

¹ This work noted that the measurement of Bedding (1993) “proved discrepant” and was not included in the orbital fit. This was based on a misreading of the epoch of Bedding’s observation; the error has been corrected in the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2006).

3 THE SUSI RESULTS

3.1 Observations in 1999

δ Sco was initially observed with SUSI using the original “blue” configuration described in Davis et al. (1999). Like most two-aperture interferometers, SUSI measures the squared modulus of the fringe visibility, and for binary stars this is given by

$$|V|^2 = \frac{|V_1|^2 + \beta^2 |V_2|^2 - 2\beta |V_1| \cdot |V_2| \cos \psi}{(1 + \beta)^2} \quad (1)$$

where

$$\psi = \frac{2\pi \mathbf{b} \cdot \boldsymbol{\rho}}{\lambda} \quad (2)$$

Here V_1 and V_2 are the visibilities of the primary and secondary respectively, $\beta \leq 1$ is the brightness ratio, \mathbf{b} is the baseline vector projected on the sky, $\boldsymbol{\rho}$ is the vector separation of the two stars, and λ is the wavelength (Hanbury Brown et al. 1970). As explained elsewhere (Davis et al. 2005), due to the difficulty of calibrating binary star observations with the original, blue-sensitive SUSI instrumentation, the observed squared visibilities, $|V_{\text{obs}}|^2$, were fitted using

$$|V_{\text{obs}}|^2 = (C - C_b t) |V|^2 \quad (3)$$

where C and C_b are fitting parameters, and t is the time. The parameters C and C_b reflect the fact that seeing diminishes the fringe visibility and that the seeing loss in general increases in a roughly linear fashion during the night.

In the case of δ Sco it was assumed that the angular diameters of the individual stars were much smaller than the angular separation and that the orbital motion during any given night was negligible. It follows that $|V_1|^2 = |V_2|^2 = 1$ and there are five fitting parameters: the angular separation ρ , the position angle θ , the brightness ratio β and the two empirical fitting parameters C and C_b .

δ Sco was observed on the nights of 29, 30, 31 May and 3 June, 1999 at a wavelength of 442 nm and a baseline of 5 m. Based on the published orbital elements the rates of change in the position angle and separation were expected to be 0.02 day^{-1} and $0.14 \text{ mas} \cdot \text{day}^{-1}$, respectively, and the variation over several nights should have been negligible compared to the observational uncertainties. The actual data, however, showed considerable night-to-night variation. It was eventually realised that this was the result of variable seeing. For each night the data were fitted using the procedure outlined above. The data were then scaled by $(C + C_b)^{-1}$ to produce “unbiased” values of $|V|^2$, and the data for the different nights were then plotted together. This immediately highlighted portions of the data that were badly affected by seeing. These data points were removed and the data refitted. After several iterations a consistent set of data was obtained for the four nights, as shown in Fig. 1. The best fit values for the angular separation, position angle and brightness ratio for the epoch J1999.4 are:

$$\begin{aligned} \rho &= 81.13 \pm 0.15 \text{ mas} \\ \theta &= 16^\circ.1 \pm 0^\circ.2 \\ \beta &= 0.195 \pm 0.005 \end{aligned}$$

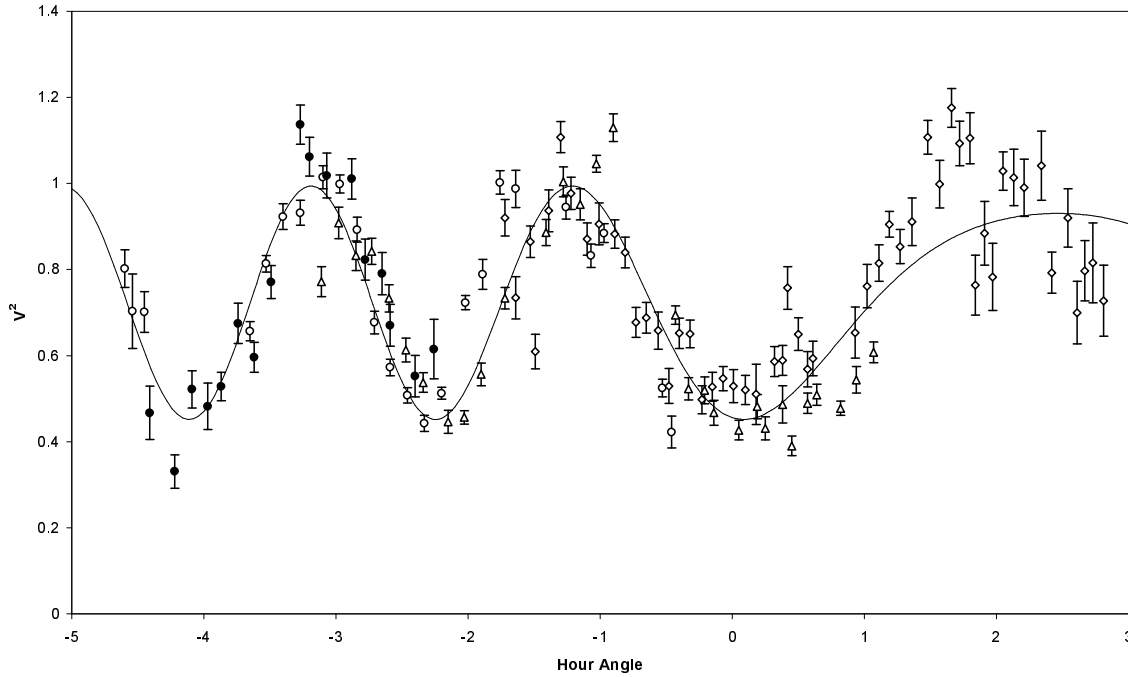


Figure 1. The SUSI data for the 1999 observations. The data from the different nights are shown as follows: 1999 May 29 (\circ), 1999 May 30 (\bullet), 1999 May 31 (\diamond) and 1999 June 06 (\triangle). The line is the best fit to the weighted data.

Table 1. The magnitude difference between the two components of δ Sco

Epoch	Difference	λ (nm)	Instrument
1971	1.9 ± 0.4	443	NSII
1991	1.5 ± 0.3	600 ^a	MAPPIT
1999	1.78 ± 0.03	442	SUSI

^aMarson, Bedding & Robertson (1992).

The brightness ratio expressed as a magnitude difference is also listed in Table 1 along with the values obtained with the NSII and MAPPIT.

3.2 Observations in 2000 and 2001

Attempts were made in 2000 to observe δ Sco using a 40 m baseline, since the angular separation was expected to be ~ 9 mas. There were two nights of data in March, five nights in May and three nights in June. The characteristic modulation expected for a binary system (see Fig. 1) was not seen, although in the case of the March data the SNR was poor due to bad seeing.

A similar attempt was made in 2001 (four nights in June and five in July). The separation was expected to be similar to that observed in 1999, but again the results were negative.

3.3 Observations in 2006 and 2007

Since the observations in 2001 SUSI has undergone a major upgrade (Davis et al. 2007). In particular, a new “red” fringe

detection system has been developed that uses a scanning mirror to sweep through a range of optical path. A wide optical bandwidth is used, and in the case of a single star a “fringe packet” is observed centred on the white-light fringe position. Fourier methods are then used to estimate $|V|^2$. For the observations reported here a bandwidth of 80 nm centred on 700 nm was used.

In the case of a binary system, each star will produce its own fringe packet and the separation between the packets will be $\Delta x = \mathbf{b} \cdot \boldsymbol{\rho}$. The width of each fringe packet is approximately $w = \lambda^2 / \Delta\lambda$, where $\Delta\lambda$ is the bandwidth, and if $\Delta x \ll w$ the two fringe packets will “beat” with each other and the overall fringe visibility will be given by equation (1). However, if $\Delta x \gg w$ the two fringe packets will be separated in optical path difference. Fig. 2 shows an example of such a double-peaked fringe envelope for the binary α Dor.² The separation between the envelopes due to the primary and secondary was approximately $45 \mu\text{m}$ when this observation was made.

In general $\mathbf{b} \cdot \boldsymbol{\rho}$ varies throughout a set of observations due to the Earth’s diurnal rotation. However, in 2006–2007 the position angle of δ Sco was $\sim 180^\circ$, making it almost parallel with the N–S baseline configuration of SUSI. As a consequence the separation of the fringe packets was expected to remain nearly constant throughout an observing session, making it easy to locate and measure the two fringe peaks. An attempt was made to observe the double-peaked

² The “fringe envelope” is the modulus of the analytic signal associated with the fringe packet. Operationally it can be found using the expression given by Bracewell (1999). The fringe envelope does not depend on the phase of the fringe packet and can be averaged over many fringe scans to improve the SNR.

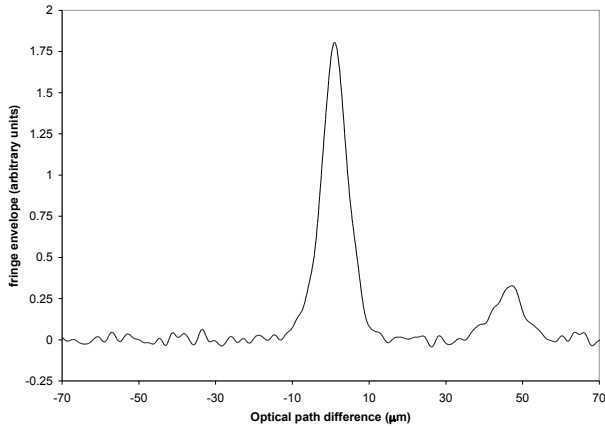


Figure 2. The mean fringe envelope for a set of fringe scans taken while observing the binary star α Dor (HD29305) on 2005 Jan 12 with a 40 m baseline at 700 nm. The envelope due to the primary is located at zero optical path difference while that of the secondary is located near $+45 \mu\text{m}$.

signal from δ Sco on the night of 30 June 2006 using a 40 m baseline. The separation was estimated to be $\sim 40 \mu\text{m}$. Only one fringe peak could be detected. The absence of the second peak could not be explained by instrumental effects or the analysis procedure, as the instrumental configuration was essentially identical to that used for the α Dor observations and the position of the secondary peak with respect to the primary was essentially the same for both stars. Atmospheric seeing was ruled out because other stars were observed the same night without any difficulties.

3.4 Discussion

Miroshnichenko et al. (2001) explained the spectroscopic and photometric behaviour of δ Sco in terms of the development of a circumstellar disk that started to form shortly before periastron. This scenario explains the brightness variations that were observed in terms of the complex evolution of this disk. This disk may have been a new phenomenon or may have grown out of the H α emitting disk seen earlier (Miroshnichenko et al. 2001; Galazutdinov & Krelowski 2006).

The interpretation of the 2005–2006 observations is straightforward. The fact that only one fringe envelope was seen implies that the primary was fully resolved; i.e., the angular size of the disk, projected onto the SUSI baseline, is $\theta_{\text{disk}} \gtrsim 1.22\lambda/b = 4.4 \text{ mas}$, where $b = 40 \text{ m}$ is the projected baseline and $\lambda = 700 \text{ nm}$ is the wavelength.

The most likely explanation for the apparent negative results obtained with SUSI in 2000 and later epochs is that the optically thick disk was fully resolved by the interferometer. This allows us to place lower limits on the angular size of the disk at the epoch of the observations.

The 2000–2001 observations were made with the blue beam-combining system. The effect of partial resolution of the primary would be to reduce the modulation seen in Fig. 1 even further. Given the noise in the data we estimate that the modulation would be undetectable if the primary were

$\gtrsim 2 \pm 1 \text{ mas}$. The relatively large uncertainty reflects the fact that the actual threshold for detecting the modulation is not well defined, as it depends on the seeing conditions.

Carciofi et al. (2006) have developed a thick disk model to account for the continuum emission. They estimated the size of the circumstellar disk in 2001 to be $7R_*$, where R_* is the radius of the primary. Using the data given by Miroshnichenko et al. (2001) $R_* \sim 6R_\odot$. Combining this with our dynamical parallax (see Section 5) the size of the disk given by Carciofi et al. (2006) corresponds to 2.8 mas . This is consistent with our measured value of $2 \pm 1 \text{ mas}$ for the same epoch (2001).

Carciofi et al. (2006) note that if the disk is geometrically thin and lies in the orbital plane it will obscure only $\sim 10\%$ of the stellar flux, but to explain the observed fluctuations in the light curve one has to assume that the geometry of the disk must change. If only $\sim 10\%$ of the primary is obscured one would expect to see an unresolved component in the interferometric data taken with the red beam-combining system in 2005–2006. The fact that no unresolved component was seen suggests that the disk was in fact the dominant contribution to the light from the primary plus disk system.

4 THE ORBIT OF δ SCO

It is clear from Fig. 5 in Miroshnichenko et al. (2001) that their orbit does not fit the interferometric data as well as the Hartkopf et al. (1996) orbit. Conversely, their Fig. 6 shows that the Hartkopf elements do not reproduce their RV curve. It is apparent from this figure that the spectroscopic data provide a very precise value for the epoch of periastron T . The symmetry of the RV curve around T also implies ω is very close to zero.

Ideally one should fit the two sets of data simultaneously and we have followed the procedure outlined by Pourbaix (1998) with a few modifications. Because δ Sco is a single-lined spectroscopic binary it is natural to choose a_A , the physical semimajor axis of the primary’s orbit in kilometres, as an additional orbital element. For convenience the fitting algorithm actually optimizes the RV amplitude K_1 ; the semimajor axis is then found using the standard relation (Heintz 1978)

$$a_A = \frac{43200 f_d P K_A (1 - e^2)^{1/2}}{\pi \sin i} \quad (4)$$

where f_d is a numerical factor depending on the units of P .³ Similarly we can also derive the mass function in solar masses:

$$f(m) = \frac{M_B^3}{(M_A + M_B)^2} = 3.985 \times 10^{-20} \frac{a_A^3}{(f_d P)^2} \quad (5)$$

or

$$f(m) = 1.03617 \times 10^{-7} \frac{f_d P K_A^3 (1 - e^2)^{3/2}}{\sin^3 i} \quad (6)$$

The Nelder & Mead (1965) simplex algorithm was used to fit the objective function, which was essentially the same as the one used by Pourbaix (1998) except that the last term

³ If P is in days, $f_d = 1$. It is equal to 365.25 or 365.242... if P is in Julian or Besselian years, respectively.

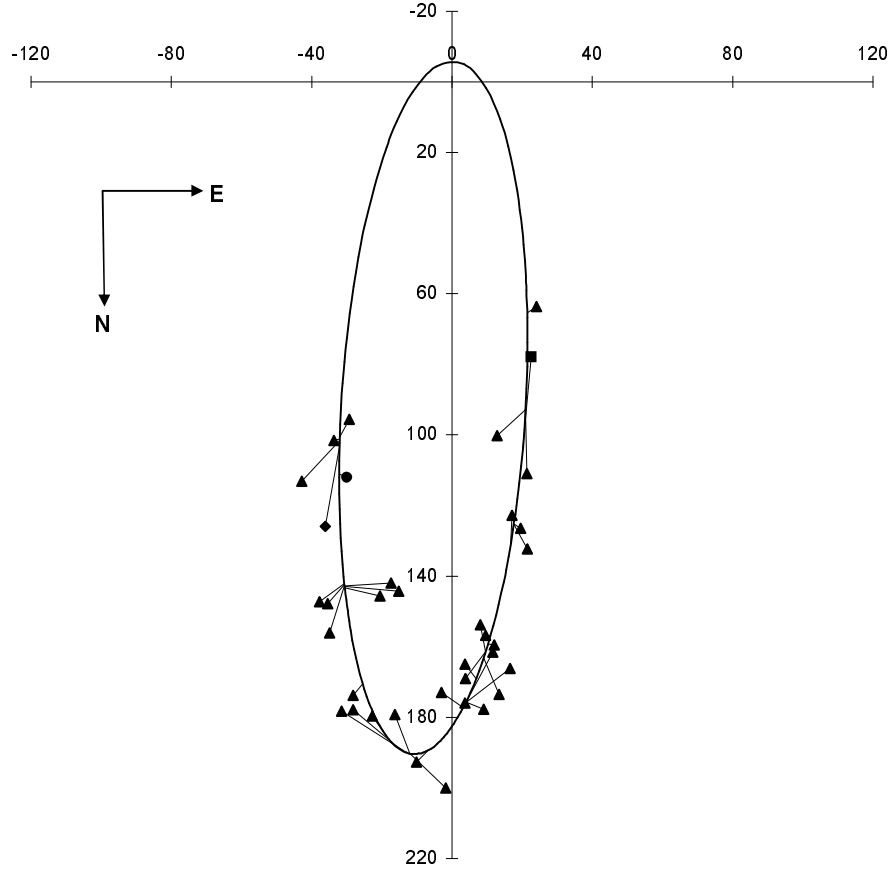


Figure 3. The interferometric orbit for δ Sco using our revised elements (see Table 2). The units for both axes are in mas. The lines indicate the O-C vectors and the symbols indicate the technique used: \blacktriangle – speckle interferometry; \blacklozenge – HIPPARCOS; \bullet – MAPPIT; \blacksquare – long-baseline optical interferometry (this work). Except for this latter point all the data are from Hartkopf et al. (2006).

Table 2. The orbital elements for δ Sco

Element	Ref. <i>a</i>	Ref. <i>b</i>	This Work
Period P (yr)	10.58 ± 0.08	10.58^c	10.74 ± 0.02
Epoch of periastron T	$B1971.41 \pm 0.14$	$J2000.693 \pm 0.008$	$J2000.69389 \pm 0.00007$
Eccentricity e	0.92 ± 0.02	0.94 ± 0.01	0.9401 ± 0.0002
Semimajor axis (mas) a''	107 ± 7	107^c	98.3 ± 1.2
Inclination i	$48^\circ 5 \pm 6^\circ 6$	$38^\circ \pm 5^\circ$	$38^\circ \pm 6^\circ$
Long. periastron ω	$24^\circ \pm 13^\circ$	$-1^\circ \pm 5^\circ$	$1^\circ 9 \pm 0^\circ 1$
Long. of asc. node Ω	$159^\circ 3 \pm 7^\circ 6$	175°	$175^\circ 2 \pm 0^\circ 6$
Systemic RV V_γ (km.s $^{-1}$)		-6 ± 0.5	-6.72 ± 0.05
RV amplitude K_A (km.s $^{-1}$)			23.84 ± 0.05
Semimajor axis of primary a_A (km)			$(7.1 \pm 0.1) \times 10^8$
Mass function $M_B^3/(M_A + M_B)^2$ (M_\odot)			0.9 ± 0.4

Ref. *a* Hartkopf et al. (1996)

Ref. *b* Miroshnichenko et al. (2001)

^c Value assumed from Ref. *a*

(the sum of the RV residuals for the secondary) was omitted. The uncertainties in the elements were estimated by Monte Carlo simulation.

All the interferometric measures (ρ , θ values) listed in Hartkopf et al. (2006) were used as well as the measure reported here. Where necessary the phases were adjusted by adding 180° to make them consistent with that found by

Bedding (1993) with phase-closure. The Besselian epochs in the Fourth Catalog were also converted to Julian epochs (this made a small but significant improvement to the fit). A total of 36 interferometric measures were used. The 30 RV values were taken from Table 3 in Miroshnichenko et al. (2001). The interferometric data span the epoch J1973.2 to J1999.4; the spectroscopic data are mostly concentrated

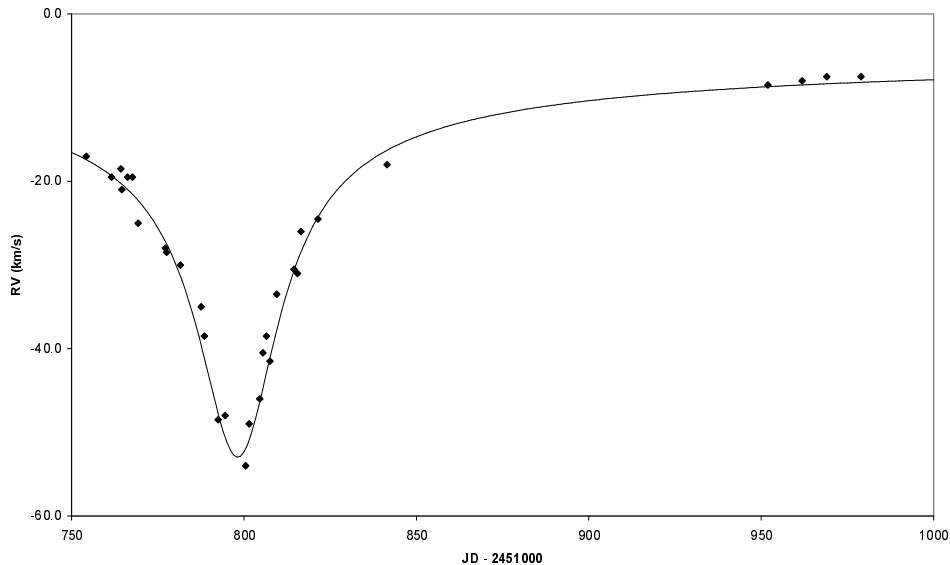


Figure 4. The RV data and the RV curve for δ Sco calculated using our revised elements (see Table 2). The points are taken from Table 3 in Miroshnichenko et al. (2001) and we have assumed that the differences between HJDs and JDs are negligible.

around the epoch of periastron, J2000.7, with four points measured near the epoch J2001.1. The initial guesses for the orbital elements were taken from Miroshnichenko et al. (2001); the initial guesses for the amplitude and the γ -velocity were 25 km s^{-1} and -6 km s^{-1} , respectively. The results of our analysis are shown in the last column of Table 2. This Table also lists the elements previously obtained by Hartkopf et al. (1996) and Miroshnichenko et al. (2001). The interferometric orbit is plotted in Fig. 3 along with the data and the “observed minus calculated” (O-C) vectors. Fig. 4 shows the RV data and the best fitting RV curve.

The most significant differences between our orbital fit and the previous ones are in the semimajor axis and the period. We found $a'' = 98.3 \pm 1.2 \text{ mas}$ and $P = 10.74 \pm 0.02 \text{ yr}$; these should be compared to the values of $a'' = 107 \pm 7 \text{ mas}$ and $P = 10.58 \pm 0.08 \text{ yr}$ found by Hartkopf et al. (1996) and assumed by Miroshnichenko et al. (2001). The other orbital elements are in excellent agreement with those found by Miroshnichenko et al. (2001), who inferred a value for i from the $H\alpha$ profile.

The most uncertain quantity is the mass function. The large uncertainty in $f(m)$ is almost entirely due to $(\sin i)^{-3} = 4.3 \pm 1.9$.

5 THE MASSES OF δ SCO A & B

The magnitude difference between the two components is $\Delta m \sim 2$, suggesting that the secondary is also an early type star. In this section we examine this in more detail and estimate the masses of the two components.

Assuming that the two stars have the same age and chemical composition, the luminosity and mass are related by the empirical mass-luminosity relation (Griffiths, Hicks & Milone 1988).

$$\log_{10}(L_B/L_A) = (3.51 \pm 0.14) \log_{10}(M_B/M_A) \quad (7)$$

We have previously used this method to determine the

masses of the two massive components of the λ Sco system (Tango et al. 2006). In that case there was strong circumstantial evidence that the stars were formed at the same time: it is a triple system and the orbits of the secondary and tertiary lie in the same orbital plane. For δ Sco there is no additional information to support the hypothesis that the two stars were formed together; indeed, the fact that the orbit is so eccentric may be evidence that the system may have suffered some kind of disruption in the past.

Because of the development of the emission region around the primary we also need to treat the brightness ratio with caution. Although Galazutdinov & Krelowski (2006) reported $H\beta$ emission prior to 1999 there is no indication of photometric brightening and we believe that the emission region was optically thin in the continuum at this time. This is supported by the data in Table 1: there are no significant differences between the Δm measured at the three epochs 1971, 1991 and 1999.

The brightness ratio was measured at 442 nm and we assume that m_{442} is equal to the B magnitude. To estimate the luminosity ratio we must know both the B-V and bolometric corrections (BC) for the two stars, but the spectral class of the secondary is unknown. We initially assumed that both stars had the same B-V and BC and used the mass-luminosity relation to make a preliminary estimate of the masses. We then used the ZAMS model grid of Tout et al. (1996) assuming solar metallicity to determine the effective temperatures from the masses. The B-V and bolometric corrections were then found by interpolating the tables in Flower (1996). The luminosity ratio was found from the experimentally determined brightness ratio β_{442} using:

$$\begin{aligned} -2.5 \log_{10}(L_B/L_A) &= -2.5 \log_{10}(\beta_{442}) \\ &\quad -(B-V)_B + (B-V)_A \\ &\quad + BC_B - BC_A \end{aligned} \quad (8)$$

This was used to estimate the next approximation for the masses and the procedure was repeated until the solution

converged. It should be noted that the interpolation formulas given by Tout et al. (1996) made this quite straightforward.

Four iterations were sufficient and we estimate the mass ratio q for the two stars to be

$$q = \frac{M_A}{M_B} = 1.957 \pm 0.011 \quad (9)$$

The individual masses can be determined from $f(m)$ and q :

$$M_A = 15 \pm 7 M_\odot \quad (10)$$

$$M_B = 8.0 \pm 3.6 M_\odot \quad (11)$$

It should be noted that the choice of a ZAMS model grid may introduce systematic errors as the δ Sco system may be somewhat evolved. However, the uncertainty in the masses of the stars is dominated by the uncertainty in the mass function and consequently more detailed modelling is not justified at present.

The colour indices for the A and B components found by the procedure outlined above are $B-V = -0.29$ and -0.25 , respectively, suggesting that the spectral type of the secondary is approximately B2 (Schmidt-Kaler 1982). This is consistent with the observation by Carciofi et al. (2006) that the spectroscopy suggests that the primary and secondary have similar effective temperatures.

Given the masses, the dynamical parallax can be found from

$$\varpi_d = \frac{a''}{P^{2/3}(M_A + M_B)^{1/3}} = 7.03 \pm 0.15 \text{ mas} \quad (12)$$

6 DISCUSSION

The revised HIPPARCOS parallax $\varpi = 6.65 \pm 0.89$ mas (van Leeuwen 2007) is in good agreement with our dynamical parallax. Our parallax allows us to determine the physical size of the δ Sco disk; we estimate its diameter to have been $\gtrsim 0.28 \pm 0.14$ AU in 2000/2001 and $\gtrsim 0.57$ AU in 2005/2006. The physical separation of the two stars at periastron is 0.84 AU.

As noted previously, Otero et al. (2001) suggested that δ Sco might be a γ Cas type variable star. These are Be stars that exhibit eruptive irregular variability, with light amplitudes reaching up to 1.5 in V (Samus et al. 2004).

The bright B0.5e star γ Cas is also a binary system that is slightly further away than δ Sco (its revised HIPPARCOS parallax is 5.89 ± 12 mas). It is well known for its unique and complex X-ray emission that consists of several distinct components. The evidence strongly suggests that the X-ray emission occurs at the Be star itself or its disk (Smith et al. 2004). The orbit was determined by Harmanec et al. (2000) to be moderately eccentric ($e = 0.260$) whilst Miroshnichenko et al. (2002) found the orbit to be circular. Although this discrepancy has yet to be resolved it is nevertheless clear that the binary characteristics of γ Cas, however, are quite different to δ Sco; in particular its orbital period is approximately 200 days. Harmanec et al. (2000) reported the mass of the γ Cas companion to be $\sim 1 M_\odot$ (Harmanec et al. 2000); according to Smith et al. (2004) the secondary is most likely a dwarf and is not a white dwarf or neutron star. In comparison, δ Sco has a highly eccentric

orbit, a period of 10.7 years and its companion is a relatively massive B2 star.

X-ray emission typical of B stars had been detected from δ Sco prior to the periastron events of 2000 (Grillo et al. 1992; Berghöfer, Schmitt & Cassinelli 1996), but we are not aware of any more recent X-ray observations. If δ Sco is analogous to γ Cas we would now expect its X-ray spectrum to exhibit some of the unusual features seen in the X-ray behaviour of γ Cas. Further work, particularly X-ray observations of this intriguing system, are needed to clarify the nature of δ Sco.

ACKNOWLEDGMENTS

The authors gratefully thank the Australian Research Council and the University of Sydney for supporting this work.

APJ and JRN acknowledge the support provided by a University of Sydney Postgraduate Award. APJ also acknowledges the support provided by a Denison Postgraduate Award.

We would like to thank the referee for his extensive and extremely helpful criticisms of the original manuscript.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

- Bedding, T. R., 1993, *AJ*, 106, 768
- Berghöfer, T. W., Schmitt, J. H. M. M., Cassinelli, J. P., 1996, *ApJS*, 118, 481
- Bracewell, R. N., 1999, *The Fourier Transform and Its Applications*, McGraw-Hill, New York
- Carciofi, A. C., et al, 2006, *ApJ*, 652, 1617
- Cote, J., van Kerkwijk, M. H., 1993, *A&A*, 274, 870
- Davis, J. et al., 2007, *PASA*, 24, 138
- Davis, J. et al., 2005, *MNRAS*, 356, 1362
- Davis, J., Tango, W. J., Booth, A. J., ten Brummelaar, T. A., Minard, R. A., Owens, S. M., 1999, *MNRAS*, 303, 773
- Dunham, D. W., 1974, *Occultation Newslett.*, 1, 4
- Flower, P. J., 1996, *ApJ*, 469
- Galazutdinov, G. A., Krelowski, J., 2006, *ApJ*, 637, 342
- Gies, D. R. et al., 2007, *ApJ*, 654, 527
- Griffiths, S. C., Hicks, R. B., Milone, E. F., 1988, *J. R. Astron. Soc. Canada*, 82, 1
- Grillo, F., Sciortino, S., Micela, G., Vaiana, G. S., Harnden, Jr., F. R., 1992, *A&ASup*, 81, 795
- Hanbury Brown, R., Davis, J., Allen, L. R., 1974, *MNRAS*, 167, 121
- Hanbury Brown, R., Davis, J., Herbison-Evans, D., Allen, L. R., 1970, *MNRAS*, 148, 103
- Harmanec, P. et al., 2000, *A&A*, 364, L85
- Hartkopf, W. I., Mason, B. D., 2006, *Sixth Catalog of Orbits of Visual Binary Stars* (v. 2006.5) (<http://ad.usno.navy.mil/wds/orb6.html>)
- Hartkopf, W. I., Mason, B. D., McAlister, H. A., 1996, *AJ*, 111, 370
- Hartkopf, W. I., Mason, B. D., Wycoff, G. L., McAlister, H. A., 2006, *Fourth Catalog of Interfer-*

- ometric Measurements of Binary Stars (v. 2006.5)
(<http://ad.usno.navy.mil/wds/int4.html>)
- Heintz, W. D. 1978, *Double Stars*, D. Reidel, Dordrecht
- Hoffleit, D., Warren, Jr., W. H., 2001, *Bright Star Catalogue*, 5th Revised Ed., Astronomical Data Center, NSSDC/ADC
- Innes, R. T. A., 1901, *MNRAS*, 61, 414
- Labeyrie, A., Bonneau, D., Stachnik, R. V., Gezari, D. Y., 1974, *ApJ. Lett.*, 194, L147
- Levato, H., Malaroda, S., Morrell, N., Solivella, G., 1987, *ApJ Sup.*, 64, 487
- Marson, R. G., Bedding, T. R., Robertson, J. G., 1992, *PASA*, 10, 71
- Miroshnichenko, A. S. et al., 2001, *A&A*, 377, 485
- Miroshnichenko, A. S., Bjorkman, K. S., Krugov, V. D., 2002, *PASP*, 114, 1226
- Miroshnichenko, A. S. et al., 2003, *A&A*, 408, 305
- Nelder, J. A., Mead, R., 1965, *Computer Journal*, 7, 308
- Otero, S., Fraser, B., Lloyd, C., 2001, *Informational Bulletin on Variable Stars*, 5026, 1
- Perry, C. L., Olsen, E. H., Crawford, D. L., 1987, *PASP*, 99, 1184
- Pourbaix, D., 1998, *A&AS*, 131, 377
- Quirrenbach, A. et al., 1997, *ApJ*, 479, 477
- Samus, N. N. et al., 2004, *VizieR Online Data Catalog*, II/250
- Schmidt-Kaler, T., 1982, in K. Schaifers, H. H. Voigt eds., *Landolt-Börnstein*, Springer-Verlag, Berlin, VI/2b
- Slettebak, A., 1982, *ApJS*, 50, 55
- Slettebak, A., 1985, *ApJS*, 59, 769
- Smith, M. A., Cohen, D. H., Gu, M. F., Robinson, R. D., Evans, N. R., Schran, P. G. 2004, *ApJ*, 600, 972
- Tango, W. J. et al., 2006, *MNRAS*, 370, 884
- Tout, C. A., Pols, O. R., Eggleton, P. P., Han, Z., 1996, *MNRAS*, 281, 257
- van Hoof, A., Bertiau, F. C., Deurinck, R., 1963, *ApJ*, 137, 824
- van Leeuwen, F., 2007, *Hipparcos, the New Reduction of the Raw Data*, ASSL Vol. 350, Springer, Dordrecht